Chapter 1
INTERIM FINDINGS AND ACCOMPLISHMENTS

1.1 INTRODUCTION

In response to the terrorist attacks of September 11, 2001, the National Institute of Standards and Technology (NIST) initiated a formal federal building and fire safety investigation of the World Trade Center (WTC) disaster on August 21, 2002. At the same time, NIST also released the final plan for its investigation.

NIST has received large amounts of data and information related to the design, construction, operation, inspection, maintenance, repair, alterations, emergency response, and evacuation of the WTC complex. A summary is included in Section 2.1. NIST has received considerable cooperation from the Port Authority of New York and New Jersey (PANYNJ or Port Authority), the City of New York, the National Commission on Terrorist Attacks Upon the United States (9-11 Commission), designers, leaseholders, contractors, suppliers, insurers, news media, tenants, first responders, survivors, and families of victims.

NIST has received all of the essential information it needs for the WTC Investigation. NIST has a few requests for materials that are lost, currently pending, or not yet located; NIST is making efforts to re-create this information from various sources since much of it was lost when the buildings collapsed. NIST continues to pursue other materials that can clarify some aspects of the Investigation.

The interim findings summarized in this progress report are based on information contained in public updates issued by NIST in December 2002 and December 2003, a previous progress report issued in May 2003, and work completed since the last progress report. (Previous updates and progress reports may be found at http://wtc.nist.gov.)

NIST expects to release the draft of the final investigation report for public comment in December 2004. **NIST is not making any recommendations at this time. All recommendations will be made in the final report.** These interim findings and the working hypothesis for the collapse of the WTC towers and WTC 7 are subject to refinement or change as further information becomes available prior to release of the final investigation report. The final report will include any recommendations that NIST considers appropriate based on these and other findings yet to be made.

NIST welcomes comments from technical experts and the public on the interim findings presented herein. Comments may be sent by e-mail to wtc@nist.gov, facsimile to (301) 975-6122, or regular mail to WTC Technical Information Repository, Stop 8610, 100 Bureau Drive, Gaithersburg, MD 20899-8610.

The interim findings are presented in four subsections that relate to the investigation objectives listed below. They are then subdivided according to the technical areas to which they relate. NIST findings are presented in *italics* to distinguish them from narrative text throughout this section.

The stated objectives contained in the NIST investigation plan are:

1. To determine (a) why and how the WTC 1 and WTC 2 collapsed following the initial impact of the aircraft, and (b) why and how the 47-story WTC 7 collapsed.

2. To determine why the loss of life and injuries were so low or so high depending on location, including technical aspects of fire protection, occupant behavior, evacuation, and emergency response.

3. To determine the procedures and practices which were used in the design, construction, operation, and maintenance of the WTC buildings.

4. To identify, as specifically as possible, areas in national building and fire codes, standards, and practices that warrant revision.

1.2 COLLAPSE OF THE WTC TOWERS

Working Hypothesis

NIST is investigating possible collapse scenarios to establish the sequence of events that led to the collapse of the WTC towers following the initial impact of the aircraft. The objectives of the NIST analysis are to determine the most probable sequence of events from the moment of aircraft impact until the initiation of global building collapse and to identify the factors that have the strongest influence on the most probable sequence.

NIST has developed a working hypothesis to explain the collapse initiation of the WTC towers. The working hypothesis (summarized below and in Appendix Q) identifies the chronological sequence of major events as the WTC tower structures redistributed loads from structural element to structural element to accommodate the aircraft impact and subsequent fire damage until no further load redistribution was possible to maintain overall stability, thus, leading to collapse. The hypothesis:

- Is based on analysis of the available evidence and data, consideration of a range of hypotheses (including those postulated publicly by experts), and a newly enhanced understanding of structural and fire behavior.

- Is consistent with all evidence currently held by NIST, including photos and videos, eyewitness accounts, and emergency communication records.

- Allows for multiple load redistribution paths and damage scenarios for each building, currently under analysis.

- Will be further refined based on the results of NIST's continuing analyses to identify specific load redistribution paths and damage scenarios that are possible for each building, from which the most probable collapse sequence will be identified.

NIST welcomes comments from technical experts and the public on the working hypothesis. Among the key questions that NIST continues to investigate within the framework of the working hypothesis are the following:

- How and why did WTC 1 stand nearly twice as long as WTC 2 before collapsing (103 min versus 56 min), though they were hit by virtually identical aircraft?
- What were the relative roles of the perimeter and core columns[1] and the composite floor system,[2] including connections, in initiating the collapses?
- What was the post-impact condition of the fireproofing, especially the extent to which fireproofing may have been damaged due to aircraft impact?
- What factors related to normal building and fire safety considerations not unique to the terrorist attacks of September 11, 2001, if any, could have delayed or prevented the collapse of the WTC towers?

In evaluating the working hypothesis for the collapse of the WTC towers, NIST is also considering the following factors:

- The relative contributions of aircraft impact damage and subsequent fires;
- How safe each building was immediately after aircraft impact but before fire weakened the structures, i.e., to what extent the capacity of the buildings to carry design loads[3] was reduced;
- Whether the undamaged towers would have remained standing in a "maximum credible fire";[4] and
- The role compartmentation (i.e. areas divided by fire-rated walls) may have played, i.e., what would have happened if the floors had been separated into 7,500 or 10,000 ft^2 compartments with 1 h fire-rated partition walls or separations.

---

[1] The perimeter columns were designed to carry both gravity and wind forces and acted together as a framed-tube system. The core columns were designed to carry only gravity loads and were not required to provide frame action.

[2] The composite floor truss system, which included long-span open-web bar joist elements, was designed to carry floor loads to the supporting core and perimeter columns. It also acted as a diaphragm that distributed wind forces to the perimeter columns of the framed-tube system and provided lateral stability to the perimeter columns.

[3] The design of the WTC towers was governed by gravity and lateral wind loads.

[4] A maximum credible fire for the WTC towers is assumed to have the following characteristics: the sprinkler system is compromised, overwhelmed, or not present; there is no active firefighting; combustible building contents averaging 10 psf (in the range of about 5 psf to 20 psf for conventional office buildings); floor-to-floor fire spread to next upper floor at 30 min or 60 min; and ventilation from windows broken by fire and a total of 50 ft^2 of air leakage between floors.

Finding 1a.1: *The following chronological sequence of major events led to the eventual collapse of the towers; specific load redistribution paths and damage scenarios for each building continue to be refined:*

- Aircraft impact damage to perimeter columns, resulting in redistribution of column loads to adjacent perimeter columns and to the core columns via the hat truss;
- After breaching the building's exterior, the aircraft continued to penetrate into the buildings, damaging core columns with redistribution of column loads to other intact core and perimeter columns via the hat truss and floor systems;
- The subsequent fires, influenced by the post-impact condition of the fireproofing, weakened columns and floor systems (including those that had been damaged by aircraft impact), triggering additional local failures that ultimately led to column instability; and
- Initiation and horizontal progression of column instability resulted when redistributing loads could not be accommodated any further. The collapses then ensued.

Aircraft Impact. Buildings are not specifically designed to withstand the impact of fuel-laden commercial airliners. However, PANYNJ documents indicate that the impact of a Boeing 707 flying at 600 mph, possibly crashing into the 80th floor, was analyzed during the design of the WTC towers in February/March 1964. While NIST has not found detailed evidence of the analysis, the documents in NIST's possession state that the postulated aircraft collision would have resulted in only local damage that would not cause collapse or substantial damage to the WTC towers. The effect of the fires due to jet fuel dispersion and ignition of building contents was not considered. The loss of life in the immediate area of aircraft impact was recognized, but the loss of life due to the growth and spread of fires and smoke was not considered. Building codes do not require building designs to consider aircraft impact.

Role of the Hat Truss System

The purpose of the hat truss was to support gravity and wind loads on the antenna. It was not designed to resist lateral forces on the towers, and, in an undamaged state, it did not have a significant role in carrying gravity loads. Lateral loads due to wind were distributed to the framed-tube system via diaphragm action of the floor system. The hat truss was connected to each perimeter face at only four points, all at the same level (at the 108th floor just below the concrete floor slab). The 47 core columns were connected to diagonal elements, heavier transfer beams, or smaller beam elements of the hat truss. Most of the core columns extended to the roof level, but four core columns, which were only minimally connected to the hat truss, terminated at Floor 110. The hat truss provided minimal redistribution of loads (less than 10 percent) from perimeter columns to core columns. Most of the load redistributed due to aircraft impact damage occurred on the external face through vierendeel action.

Finding 1a.2: *The two WTC towers withstood the initial impact of virtually identical aircraft (Boeing 767-200ER) during the terrorist attacks of September 11, 2001. The robustness of the perimeter frame-tube system and large dimensional size of the WTC towers helped the buildings withstand the aircraft impact. The WTC towers displayed significant reserve capacity, vibrating immediately following impact with amplitudes that were about half the amplitudes for design wind conditions expected by the building designers. WTC 2, which collapsed first and in about half the time as WTC 1, vibrated for over 4 min at an oscillation period nearly equal to that measured for the undamaged building. The lightly damped (about 1.2 percent of critical damping) oscillation had an initial amplitude of approximately 20 in at the roof level, where expected sway was about 3 ft to 4 ft under design wind conditions.*

Aircraft Impact Damage to Perimeter Columns. Based on the above information, structural damage to perimeter columns as a result of aircraft impact of the framed-tube system appears to have played a minimal role in initiating the collapse. Perimeter column bowing prior to collapse occurred on other faces (i.e., fire floors on the south face of WTC 1 and east face of WTC 2) that were not severed by the aircraft.

Aircraft Impact Damage to Core Columns. The core columns were designed to carry only gravity loads and not required to provide frame action. The aircraft trajectory at impact suggests damage to the core columns occurred as follows:

WTC 1—The aircraft was traveling about 450 mph and hit the tower near the center of the north face damaging Floors 93 to 99. The aircraft fully entered the core area and severed or damaged central core columns in the north-south direction. Aircraft and building debris accumulated in the remaining core area and south-side floor areas as contents were displaced from the point of impact.

WTC 2—The aircraft was traveling about 550 mph and hit the tower near the southeast corner of the building damaging Floors 77 to 85. Core columns to the south and east were severed or damaged. Aircraft and building debris accumulated in the core area and floor areas to the east and north.

Severed core columns redistributed their loads in three ways, depending on how many and which core columns were severed.

1. Isolated core columns were severed. Severed column and tributary floor loads, at and above the point of impact, were redistributed locally at each floor to adjacent intact core columns via core floor framing. This was limited by shear/bending capacity of floor-framing connections to adjacent columns.

2. Critical (e.g., corner) core columns and/or several other core columns were severed. The severed column and tributary floor loads, at and above impact floors, redistributed to intact core columns via the hat truss. Significant hat truss deflections may have occurred if there was adequate connection capacity since the severed core columns and the associated floors were hanging from the hat truss which was not designed to carry such loads. This was limited by the tensile capacity of bolted splices in the severed core columns, tensile/compression capacity of hat truss members, and tensile capacity of column connections to the hat truss.

3. Extent of core column failures precluded redistribution through the hat truss and/or exceeded redistribution capacity of the hat truss. Severed column and associated floor loads, at and above floors of impact, redistributed to intact core and perimeter columns via the core and composite truss floor system. Floors were subjected to combined bending and diaphragm action (e.g., consider the scenario of no core columns in the floor span direction to visualize this action). The overall capacity of the floors was limited by shear capacity of floor-to-column connections (including perimeter columns) and tensile/bending capacity of composite truss floor connections to core or perimeter columns. Significant sagging of the hat truss system may have occurred if its capacity was exceeded.

Relative Roles of Fires and Aircraft Impact

Finding 1a.3: *Fires played a major role in further reducing the structural capacity of the buildings, initiating collapse. The tower structures withstood the initial aircraft impacts and remained stable. While aircraft impact damage did not, by itself, initiate building collapse, it contributed greatly to the subsequent fires by:*

- Compromising the sprinkler and water supply systems;
- Dispersing jet fuel and igniting building contents over large areas;
- Creating large accumulations of combustible matter containing aircraft and building contents;
- Increasing air supply into the buildings (through broken windows and holes in the sides of the buildings, and between floors due to damaged floors, vertical shafts, and columns) that permitted significantly higher energy release rates than would normally be seen in ventilation-limited building fires, allowing the fires to spread rapidly within and between floors; and
- Damaging ceilings that enabled "unabated" heat transport over the floor-to-ceiling partition walls and to the floor trusses, spandrels, and tops of columns.

Finding 1a.4: *The jet fuel, which ignited the fires, was mostly consumed within the first few minutes after impact. The fires that burned for almost the entire time that the buildings remained standing were due mainly to burning building contents and, to a lesser extent, aircraft contents, not jet fuel.*

Thermal Effects on Columns and Floors. Some floors in WTC 2 experienced partial collapse due to aircraft impact. For example, partially collapsed floor slabs were visible on the east and north faces. This included failures at the edges with perimeter columns causing floor edge sagging. Based on photographs or videographs there is no visible evidence of partially collapsed floors in WTC 1.

Role of Fireproofing

The post-impact condition of the fireproofing played a key role in the structural response to fires. The post-impact condition of the fireproofing depends on the condition of the fireproofing prior to aircraft impact and the extent to which fireproofing was damaged due to aircraft impact. The fire-affected floors in WTC 1 had, in general, upgraded or thicker fireproofing (1.5 in. specified) while, in general, those in WTC 2 did not have upgraded fireproofing (0.5 in. specified).

Fires may have had the following thermal effects:

- Core columns and core floors may have been further weakened, with reduced ability to carry and/or redistribute load, causing such loads to be redistributed to other core and perimeter columns consistent with the residual reserve capacities of these columns and the transfer mechanisms (i.e., hat truss and floor system).
- The floor system may have been further weakened, either along the span of the floor system or localized at connections with columns. The weakening floor system may have pulled the perimeter columns inward (observed on the south face of WTC 1 and the east face of WTC 2 minutes prior to building collapse) and then initiated connection failures at perimeter or core columns.

- Perimeter columns may have been further weakened, with reduced ability to carry loads. Thermal effects could also cause inward bowing of perimeter columns due to differential temperatures between the inner and outer faces of the columns. The loads that could no longer be carried by the weakened columns would have been redistributed to adjacent perimeter columns.

Column Instability and Collapse Initiation. The perimeter columns were designed as part of a framed-tube system to carry both gravity and wind forces. Instability of perimeter columns resulted from a combination of (1) redistributed loads from the core columns via the floor system and possibly the hat truss, (2) inward bowing due to thermally-weakened and sagging floors, (3) increased unsupported length due to failed floors, and (4) thermal effects directly on the perimeter columns.

The instability of a few perimeter columns was observed to propagate across the entire face and around the corners just before or during collapse initiation. The initiation or spread of perimeter column instability also may have been facilitated by the hoop stress demand on the framed-tube system exceeding the capacity of the spandrels (horizontal steel plates) that tied the perimeter columns together (e.g., at the northeast corner of WTC 2).

The initiation of global collapse for both towers was first observed by the tilting of the sections above the impact regions of both WTC towers. The tilting and the propagation of column instability are synchronous processes that initiated global collapse. The tilting may have caused forces such as shear and torsion to spread the column instability laterally.

Issues Being Investigated. Over the next few months, NIST will continue to investigate the following technical issues and modify its working hypothesis as needed. Findings on these issues will be included in the final report.

- Aircraft impact damage to structural components, fireproofing, and hat truss connections.
- Distribution of aircraft/building contents.
- Thermal effects on core columns and core floors, especially extent of fires and growth history.
- Thermal effects on welded perimeter columns, especially temperature gradients on columns.
- Extent of load redistribution to intact core columns and their reserve capacity to accommodate thermal loads.
- Capacity of hat truss connections to perimeter columns, especially to meet the demands of aircraft impact and any torsional effects.
- Capacity of hat truss to accommodate the load redistribution from severed columns.
- Capacity of bolted splices in the severed core columns to carry loads to the hat truss.
- Relative magnitude of the load redistribution provided by the local core floor, hat truss, and the core-truss floor system for each tower.

- Axial/shear/bending capacity of floor connections to core and perimeter columns.
- Effect of localized fires on floor truss connections.
- Mechanisms to propagate instability laterally in the perimeter columns (e.g., shear and torsion forces induced by a rigid body movement)
- Capacity of spandrels, including splices, to carry shear transfer in the framed-tube system, especially at the corners.
- Role of bolted splices on instability of perimeter columns.
- Outward bowing of perimeter columns due to thermal expansion of floors.
- Effect of uneven floor thermal expansion on perimeter column instability due to potential biaxial bending.
- Comparison and reconciliation of working hypothesis with observed facts (photographs and videos, eyewitness accounts, emergency communication records).
- Examination of other possible or probable hypotheses.

Visual Observations

Photographic and video images of damage and fires in the WTC buildings are providing critical guidance for the investigation. NIST has collected and assembled the visual materials into a searchable computerized database. The database now contains well in excess of 6,000 photographs representing the work of more than 185 photographers, and 150 hours of video from most of the major media outlets and more than 20 individuals.

Based on an analysis of this visual evidence, NIST has identified significant events for WTC 1 and WTC 2 related to aircraft impact, fire development, and building damage, and work is progressing on WTC 7. As part of this analysis, NIST has developed detailed mappings and time-dependent visualizations for fire, smoke, and window conditions of the WTC towers, and similar efforts are nearing completion for WTC 7.

Finding 1a.5: *On the east face of WTC 2, what appears to be the 83rd floor slab was seen hanging across window openings over a large fraction of the 82nd floor. The object was observed in a number of photographs and videos very shortly after the plane strike and found to sag further prior to collapse. On the north face of WTC 2, shorter lengths of what appear to be the 81st, 82nd, and 83rd floor slabs were seen hanging through the windows in the floors below. There was no visible evidence of floors sagging in WTC 1. NIST continues to investigate what role aircraft impact and subsequent fires had on causing such floor failures.*

Finding 1a.6: *Several minutes (less than 10 min) prior to building collapse, inward bowing of about a quarter to a third of the perimeter columns was observed in photographs on the south face of WTC 1 and the east face of WTC 2 in regions that contained active fires.*

Finding 1a.7: *At 9:36 a.m. an occupant of WTC 2 called the New York City 911 telephone operator and reported that a floor in the 90's had collapsed underneath them and that they were now on the 105th floor. The NYPD aviation unit observed the following events with respect to WTC 2. At 9:49 a.m., they reported "large pieces" falling from WTC 2. At 9:58 a.m., it was reported that the south tower was coming down. With respect to WTC 1, at 10:06 a.m., an advisory was transmitted by the aviation unit that it wasn't going to take much longer before the north tower comes down and to pull emergency vehicles back from the building. At 10:20 a.m., the unit reported that the top of the (north) tower might be leaning. At 10:21 a.m., they reported that the north tower was buckling on the southwest corner and leaning to the south. At 10:27 a.m., a report was made that the roof was going to come down very shortly.*

Finding 1a.8: *The initiation of global collapse was first observed by the tilting of building sections above the impact regions of both WTC towers. WTC 1 tilted to the south (observed via antenna tilting in a video recording), and WTC 2 tilted to the east and south and twisted in a counterclockwise motion. The primary direction of tilt was around the weak axis of the core (north-south for WTC 1 and east-west for WTC 2). An earlier building performance study, performed by a private-public sector team with funding support from the Federal Emergency Management Agency (FEMA), concluded that the core failed first in WTC 1 based on vertical movement of the antenna observed in a video recording from due north that did not capture the antenna tilt due to the angle from which the video was shot. NIST is reevaluating this conclusion based on new visual information available from a different angle.*

Analysis of Recovered WTC Steel

NIST believes the collection of steel in its possession is adequate for purposes of analyzing the quality and properties of steel for the Investigation. NIST has 236 pieces of steel in its possession. The regions of impact and fire damage were emphasized in the selection of steel pieces for the investigation. As a result, NIST has all 14 specified steel grades for the exterior panels in the WTC towers, 2 specified grades that represent 99 percent of the core columns, and both specified grades for the steel trusses that comprised the composite floor truss system.

Finding 1a.9: *Analysis of steel recovered from the WTC towers, based on stampings on the steel and mechanical tests, indicates that the correct specified materials were provided for the specified elements. When these data were combined with pre-collapse photographic images of damaged steel, it was found that aircraft impacted pieces of steel recovered from WTC 1 were in the precise locations as specified in the design drawings.*

Finding 1a.10: *Metallography and mechanical property tests indicate that the strength and quality of the steel used in the towers was as specified, typical of the era, and likely met all qualifying test requirements. Further metallographic and fractographic analyses on the pieces from the impact zone are being considered.*

Finding 1a.11: *The room-temperature strength of the steel used in the towers met the relevant standards and, in many instances, exceeded the requirements by 5 percent to 10 percent. Ten different steel companies fabricated structural elements for the WTC towers, using steel supplied by at least eight different suppliers; four fabricators supplied the major structural elements from the 9th to the 107th floors. Work is ongoing to analyze the performance of the steel building components under impact and fire conditions up to initiation of global building collapse.*

Reconstruction of the Fires

NIST has completed three series of large-fire tests to enhance and validate the fire dynamics and thermal modeling tools being used in the WTC investigation, including:

- Single office workstation cubicle fire tests, based on descriptions of furnishings used in the WTC 1 office space, to generate a database on the thermo-physical properties of the materials for input to the fire dynamics simulation tool. The effects of debris and jet fuel on these fires were also investigated.

- Fire tests of multiple WTC workstation cubicles to validate the model predictions of the sensitivity of fire intensity, duration, and spread to the distribution and nature of the combustibles, effect of ventilation on the fire, and the effects of debris and jet fuel.

- Fire tests to measure the thermal environment (heat release and transfer rate to compartment gases) in a burning compartment and to establish a data set to validate the prediction of the temperature rise of structural steel components (similar to WTC steel trusses and columns, with and without fireproofing).

In addition, NIST has completed a series of experiments on ceiling tile systems similar to those present in the WTC towers. Shake table experiments were conducted to determine the magnitude of impulses that could result in damage to the ceiling tile systems, increasing the accessibility of the fire energy to the ceiling/floor membranes.

NIST has significantly enhanced the capabilities of computational tools for fire dynamics and thermal modeling and validated their predictions during the investigation. The tools can now be applied with greater confidence to recreate possible fires from the complex arrays of combustibles that existed in the WTC buildings, given initial damage conditions and descriptions of combustibles that have been collected by NIST. Key enhancements include: underventilated fire scenarios, charring materials such as those comprising much of the office furniture, fire spread, dimensional resolution in the vicinity of structural components, time-efficient computations for large simulations, and visualization of large data sets. These tools will help to improve the fire-safe design of new structures and analyze conditions of existing structures.

Finding 1a.12: *Unlike the jet fuel that was mostly consumed in only a few minutes, typical office furnishings were able to sustain intense fires for at least an hour on a given WTC floor. NIST has obtained generic and, in some cases, specific information about the furnishings in the WTC offices. In addition, NIST has obtained descriptions of the combustible contents of the aircraft. This includes cabin materials, aircraft components, and cargo bay contents. Based on a review of this information, NIST has found that:*

- *The typical WTC office floor, using modern workstation furnishings, had on average about 4 pounds per square foot (psf) of combustible materials on floors without unusual file rooms, film storage, etc. For conventional office buildings, the weight of combustibles varies from a combustible load commensurate with that in the WTC to about 10 psf to 20 psf when there are extensive bookcases, file storage, etc.*

- *The mass of the aircraft solid combustibles was significant relative to the mass of the building combustibles in the immediate impact region of each of the WTC towers.*

Following the experimental validation of the NIST Fire Dynamics Simulator for the WTC application, an extensive series of simulations of the fire floors in all three buildings is well underway. Input to the simulations includes the information gathered on the layouts of the floors, ventilation through the broken windows (as observed in the visual collection), the nature and loading of the combustible contents of the buildings, and preliminary (visual) estimates of damage to the towers from the aircraft impact. Alternative estimates of possible damage conditions in the interiors of the buildings are examined parametrically.

Consistent with available photographic and videographic evidence, these simulations have been able to capture the broad patterns of fire movement around the floors, with the flames in a given location lasting for about 20 min before spreading to adjacent, yet unburned combustibles. This spread is generally continuous due to the relatively even distribution of combustibles and the paucity of interior partitions and tends to be controlled by the air supply available through broken windows. There are some observed instances where fires persisted over longer durations in regions with accumulated combustible debris and other instances of sudden or interrupted fire spread. To the extent that these fires are locally of high intensity and duration and occur in a vicinity where they could contribute to structural weakening, they are being examined further via additional simulations.

Applying the 1968 NYC Building Code, the WTC towers were required to have 1 h fire-rated tenant separations, but the code did not impose any minimum compartmentation requirements (e.g., 7,500 ft^2) to mitigate the horizontal spread of fire in buildings with large open floor plans. The affected floors in the WTC towers were mostly open—with a modest number of perimeter offices and conference rooms and an occasional special purpose area. Some floors had two tenants, and those spaces, like the core areas, were partitioned (slab to slab). Photographic and videographic evidence confirms that even non-tenant space partitions (such as those that divided spaces to provide corner conference rooms) provided substantial resistance to fire spread in the affected floors. Exit access corridors had a 2 h fire-rating with 1 1/2 h fire-rated doors. Enclosures for vertical exits, exit passageways, hoistways, and shafts were required to be 2 h.

Finding 1a.13: *Laboratory experiments show that impulses like those estimated for the aircraft impact caused serious damage to the ceilings in the WTC towers. This is consistent with the accounts of survivors from floors below the impact region. This damage enables "unabated" heat transport over the floor-to-ceiling partition walls and to the steel trusses, spandrels, and tops of columns.*

Structural Response and Collapse Analysis

NIST has developed and adopted a comprehensive approach to identify the most probable of technically possible collapse sequences, from aircraft impact to collapse initiation. The approach:

- Combines mathematical modeling, well-established statistical and probability-based analysis methods, laboratory experiments, and analysis of photographic and videographic evidence.

- Allows for evaluation and comparison of possible collapse sequences based on different damage states, fire paths, and structural responses.

- Accounts for variations in models, input parameters, analyses, and observed events.

NIST has defined detailed requirements for this complex series of analyses, formulated detailed modeling approaches to capture important structural behavior, made significant progress in developing and evaluating the adequacy of the models, and obtained results from preliminary analyses using the models. The objective of the analyses is to simulate highly-complex failure modes at the component level, subsystem level, and over the entire structure due to aircraft impact and the subsequent fires. In many instances, NIST is testing the limits of current engineering software. Most such systems are used in general practice for design purposes, not for high-fidelity modeling and failure analysis of complex systems.

The computational models developed by NIST include:

- A detailed model of a typical truss-framed floor of the WTC towers with over 40,000 elements and 166,000 degrees of freedom.

- A detailed model of a typical beam-framed floor of WTC towers with over 12,000 elements and 35,000 degrees of freedom.

- A detailed global model of WTC 1 with over 80,000 elements and 218,000 degrees of freedom (with 17 flexible and other rigid diaphragm floors).

- A similar detailed global model of WTC 2 with over 78,000 elements and 200,000 degrees of freedom.

- A model of a typical turbofan engine of the Boeing 767-200ER aircraft with over 60,000 elements and 100,000 nodes.

- A comprehensive model of the Boeing 767-200ER aircraft, including engines, airframe, landing gear, fuel tanks, passenger cabin, and cargo bay, with over 530,000 elements and 740,000 nodes.

The first four models described above are being used to evaluate the baseline performance of the WTC towers under design gravity and wind loads. They also serve as *reference* models for other phases of the investigation involving analyses of aircraft impact damage and response of the thermally-insulated WTC structures to the subsequent fires.

Finding 1a.14: *The WTC tower structures represented an innovative structural system when they were built. The structural system incorporated many new and unusual features, including:*

- *First frame-tube framing system for a high-rise steel building.*

- *Composite floor system, using open-web bar joist elements, to provide lateral stability and diaphragm action.*

- *First extensive use of prefabricated perimeter panels (3 columns wide by 3 stories high) in steel construction with bolted butt-plate column splices.*

- *Uniform perimeter column geometry (14 in x 14 in cross-section) over most of the height of the 110-story buildings.*

- *First use of more than 14 different grades of specified steel in a tall building, with 14 grades specified for the uniform perimeter column geometry.*

- *Use of deep spandrel plates as beam elements connecting perimeter columns, enabling frame-tube action by providing lateral bracing around the structure.*

- *First use of wind tunnel testing to estimate the lateral wind loads in the design of a super tall building.*

- *First use of structural dampers to control dynamic motion in tall buildings, especially those due to winds (10,000 viscoelastic dampers were installed in each building connecting the floor trusses to the perimeter frame-tube system).*

- *Use of specially designed prefabricated panels to transfer forces at the chamfered corners of the frame-tube system.*

Finding 1a.15: *NIST has completed a preliminary stability analysis of the WTC towers. The findings from the preliminary analysis, if they remain viable upon further more detailed analysis, suggest that:*

- *For global instability of the WTC tower to occur under service loading conditions, five floors must have separated completely from all columns if the columns are at room temperature or four full floors must separate if the columns are uniformly heated to 600 ºC. Linear stability analysis indicates that some individual core columns begin buckling with fewer "failed" floors at both temperatures without significantly affecting global stability.*

- *For typical truss-framed floors under service loading conditions, if fifteen core columns are assumed severed due to aircraft impact, tension is induced in those columns by the floor immediately above the failure location of the columns. The tension force increases as more floor loads are picked up by the columns as they approach the hat truss at the roof level. The increase in tension load is limited by the tensile capacity of the column splice. When the tensile load exceeds the column splice capacity at a certain floor level, the splice fails, and all floors below the failed splices must redistribute their own loads directly to neighboring undamaged core columns. When fewer (only eight) core columns are assumed severed, the tension forces in the core columns are smaller due to the larger stiffness of the damaged floor area for eight severed columns, relative to that for 15 severed columns. The stiffer floor area redistributed more of the floor loads directly to neighboring undamaged core columns. The extent to which the severed core columns assist in transferring loads via the hat truss without failure of the column splices is sensitive to the relative magnitudes of the floor loads, column tension force, and column splice capacity.*

- *WTC 1 maintained stability after aircraft impact, with the highest stressed elements being the perimeter columns next to the region where columns and spandrels were severed on the north face of the tower. The analysis assumed eight columns in the core were severed due to aircraft impact. A "pushdown" analysis was used for evaluating structural stability accounts*

> *for geometric and material nonlinearities with plastic hinges. WTC 1 also maintained stability with remaining residual reserve capacity when additional perimeter columns were removed on the south face to represent the inward bowing observed in videos a few minutes prior to collapse. However, loss or weakening of additional core columns, weakening of additional perimeter columns, or loss of additional floors would be needed for global collapse of the tower to occur.*

NIST has completed a series of preliminary aircraft impact analyses using component-level models of tower perimeter and core columns with wing section and engine component models as impactors. These models were used to develop the simulation techniques required for the global analysis of the aircraft impacts into the WTC towers.

Finding 1a.16: *A 500 mph engine impact against an exterior wall panel results in a penetration of the exterior wall and failure of impacted perimeter columns. If the engine does not impact a floor slab, the majority of the engine core remains intact through the exterior wall penetration with a reduction in velocity between 10 percent and 20 percent. The residual velocity and mass of the engine after penetration of the exterior wall is sufficient to fail a core column in the event of a direct impact. Interaction with additional interior building contents prior to impact, or an indirect impact against the core column, could change this result.*

Finding 1a.17: *A normal impact of the exterior wall by an empty wing segment (toward the wing tip region) will produce significant damage to the perimeter columns, but not necessarily complete failure. This is consistent with photographs showing the exterior damage to the towers immediately after impact. Specific details of the damage depend on details of the impact orientation and locations of internal wing components such as control surface actuators and arms.*

Finding 1a.18: *Impact by a fuel-filled wing section (away from the wing tip toward the fuselage) results in extensive damage to the exterior wall panel, including complete failure of the perimeter columns. This is also consistent with photographs of the exterior damage. The resulting debris propagating into the building maintains the majority of the initial momentum of the wing prior to impact.*

NIST has completed detailed preliminary analyses of the response of a single floor truss assembly if it were subjected to a severe fire. These include the response of the truss and its seat connections (to columns) and knuckles (to provide composite action with the concrete floor slab) to service load conditions, uniformly increasing elevated temperatures in the steel, and increasing the temperature gradient in the concrete slab. The truss model includes all potential failure modes that may occur under loading and thermal conditions, though the actual sequence of failure may differ under other fire conditions.

Finding 1a.19: *NIST's preliminary analyses of a single floor truss assembly if it were subjected to a severe fire suggest the following sequence of events:*

- *The floor truss first experiences increasing vertical deflections at mid-span as it pushes (expands) outward and exerts a compressive lateral load on the exterior column. The exterior column begins to displace outward at the floor connection.*

- *Web diagonals begin to buckle at 340 ºC, the mid-span deflection continues to increase, but the horizontal displacement of the exterior column begins to decrease. The maximum horizontal displacement of the exterior column is approximately 0.7 in. when the diagonals begin to buckle. (The interior column is assumed to have no lateral displacements at the floor level, as it is braced by the core framing.)*

- *The shear connectors (steel-knuckle-to-concrete slab connections referred to as knuckles) at each end of the truss begin to fail as the steel and bottom surface of the slab reach 400 ºC, with such failures moving progressively inward from the truss ends. The failure of web diagonals and knuckles at the ends of the truss reduce the bending rigidity of the floor truss at the ends, further increasing the floor sag and decreasing the lateral outward force exerted on the columns.*

- *The truss bearing angle slips until the bolt is bearing against the edge of the slotted hole. The bolt shears off at the interior seat connection at approximately 500 ºC. The floor truss sag increases to 20 in. when the bolt fails.*

- *The interior end of the reinforced slab continues to carry vertical loads as the truss bearing angle continues to slip. At 560 ºC, the exterior column begins to be displaced inward as the floor truss continues to sag and exert vertical and horizontal tensile loads.*

- *At 650 ºC, the truss slides off the interior seat, followed by the gusset plate fracture at the exterior connection at 660 ºC.*

NIST has developed a rigorous technical approach to evaluate the role fireproofing conditions may have played in the collapse of the WTC towers, considering:

- Specified spray-applied fire resistive material (SFRM) and thicknesses for the various structural components.

- The as-built condition of the fireproofing prior to September 11, 2001, including the average SFRM thicknesses applied to different structural components, and variability in the thickness along the length of components.

- The mechanical and thermal properties of the fireproofing materials, including adhesive and cohesive bond strengths, and temperature-dependent heat capacity and thermal conductivity.

- The extent to which fireproofing may have been damaged due to aircraft impact via debris impact and local deformation/acceleration of structural components.

Finding 1a.20: *Available records suggest that the fireproofing of the columns, beams, and spandrels of the WTC towers was not a subject of concern to the building owner and designers, while fireproofing of the floor trusses was the focus of continuous reassessment and revision.*

- *The WTC towers were identified as Occupancy Group E – Business, and classified as Construction Class IB in accordance with the 1968 New York City Building Code. This* *classification required that the columns and floor systems of the towers have a 3 h and 2 h fire endurance, respectively.*

- *The steel trusses that supported the floors of WTC 1 and WTC 2 were specified to be fireproofed with 1/2 in. of SFRM, although the technical basis for the selection of fireproofing material and its thickness are not known.*
- *In 1999, a decision was made to begin upgrading the fireproofing to a specified 1.5 in. thickness as tenant spaces became unoccupied. In general, the floor systems in WTC 1 subject to aircraft impact and subsequent fires had been upgraded by September 11, 2001; the affected floors in WTC 2 had not.*
- *The fire protection of a truss-supported floor system by directly applying spray-on fireproofing to the steel trusses was innovative and not consistent with prevailing practice at the time the WTC towers were designed and constructed. While the benefits of conducting a full-scale fire endurance test were recognized by the building designers, no tests were conducted on the floor system used in the WTC towers to establish a fire endurance rating.*

Finding 1a.21: *The response of a structural component to fires is sensitive to variability in fireproofing thickness along its length. Such variations can be random in nature or in some instances as stark as bare spots. In the case of random variations, given an average fireproofing thickness and a coefficient of variation, it is possible to identify an equivalent uniform thickness without variation that gives nearly the same time history of temperature rise and component structural response under thermal loads.*

- *For the original fireproofing in the WTC towers, the as-applied fireproofing thickness (0.75 in. average and 0.4 coefficient of variation) on the floor trusses is thermally equivalent to a uniform thickness of 0.6 in. with no variation. This uniform thickness is greater than the specified minimum thickness of 0.5 in.*
- *For the upgraded fireproofing in some floors of the WTC towers, the as-applied upgraded fireproofing thickness (2.5 in. average and 0.24 coefficient of variation) is thermally equivalent to a uniform thickness of 2.2 in. with no variation. This uniform thickness is greater than the specified minimum thickness of 1.5 in.*
- *Thus, it is possible to evaluate if the as-applied average fireproofing thickness and variation on a component is thermally equivalent to a uniform thickness that is at least equal to the minimum fireproofing thickness specified on that component.*
- *For a specified fireproofing thickness, it is also possible to recommend an as-applied average thickness, given the expected variability (coefficient of variation) in quality of fireproofing application.*

NIST is currently examining an alternative performance criterion for determining the equivalent thickness based on restrained conditions to confirm the above finding.

Finding 1a.22: *Based on simplified analytical models, it was found that acceleration of a structural element, on the order of 100 times the acceleration due to gravity (or 100 g), would be required to* *dislodge 1 in thick SFRM from a planar surface. Acceleration on the order of 150 g would be required to dislodge a similar thickness of SFRM from a 1 in. diameter bar. In both cases, SFRM cohesive and adhesive strength properties and densities were typical of those used in the WTC towers. Experiments are underway to verify the results of these simplified analyses. In addition, analytical studies are underway to estimate the magnitude of accelerations of the structural members due to aircraft impact, from which the regions where fireproofing may have been dislodged will be identified.*

1.3 COLLAPSE OF THE 47-STORY WTC 7 BUILDING

Working Hypothesis

A working hypothesis has been developed around four phases of the collapse of WTC 7 that were observed in photographic and videographic records: an initiating event, a vertical progression at the east side of the building, a subsequent horizontal progression from the east to the west side of the building, and global collapse. The working hypothesis will be revised and updated as results of ongoing, more comprehensive analyses become available. NIST welcomes comments from technical experts and the public on this working hypothesis.

Finding 1b.1: *The working hypothesis for the collapse of the 47-story WTC 7, if it remains viable upon further analysis, suggests that it was a classic progressive collapse that included:*

- *An initial local failure at the lower floors (below floor 13) of the building due to fire and/or debris induced structural damage of a critical column (the initiating event), which supported a large span floor bay with an area of about 2,000 ft^2;*
- *Vertical progression of the initial local failure up to the east penthouse, as large floor bays were unable to redistribute the loads, bringing down the interior structure below the east penthouse; and*
- *Horizontal progression of the failure across the lower floors (in the region of floors 5 and 7, that were much thicker than the rest of the floors), triggered by damage due to the vertical failure, resulting in disproportionate collapse of the entire structure.*

WTC 7 Steel

No steel from WTC 7 has been identified from the pieces of recovered WTC steel in NIST's possession. WTC 7 had two specified grades of steel for columns and beams and four grades of steel for cover plates used in built-up columns. The specified grades (ASTM A36, A572 Grades 42 and 50, and A588 Grades 42 and 50) of steel are readily available. Properties were estimated from available test data in the literature.

Visual Observations

Finding 1b.2: *The first exterior sign of structural failure in WTC 7 was the sinking of the east penthouse roof structure into the building. Photographic and videographic records taken from the north have provided information about the sequence of failure events and their relative times. Other key observations* *include window breakage along the east side of the north face, occurring almost simultaneously with the sinking of the east penthouse structure, an approximate 5 s delay before the other roof structures also sank into the building core, a second set of window breakage along the west side of the north face occurring simultaneously with the other roof structure movements, and the appearance of the entire north façade above the 13th floor dropping as an intact unit 8 s after the east penthouse movement was first detected.*

Finding 1b.3: *Witnesses reported structural damage to WTC 7 on its south face and southwest corner from WTC 1 debris. A multi-story gash that extended across approximately a quarter to a third of the south face, in the lower portion of the face, was reported by a number of individuals, though details vary. This damage extended to the core area as two elevator cars were reportedly ejected from the elevator shaft at floor 8 or 9. Reported damage to the southwest corner was confirmed visually in photographic records, which show approximately two columns and related floor areas missing from floors 8 to 18. Multiple photographic and videographic records also appear to show damage on the south face that started at the roof level and severed spandrels between exterior columns near the southwest corner for at least 5 to 10 floors. However, the extent and details of this damage have not yet been discerned, as smoke is present in the photographs.*

Finding 1b.4: *Fires were first observed in WTC 7 after WTC 1 collapsed. Fires, or evidence of fires, were observed initially on the south face and near the southwest corner on Floors 22, 29, and 30. Many of these fires appeared to burn out before 2:00 p.m. Around 2:00 p.m., fires were observed in photographic and videographic records to be burning across Floors 11 and 12 on the east face, from the south to the north. Around 3:00 p.m., fires were observed on Floors 7 and 12 along the north face. The fire on Floor 12 appeared to bypass the northeast corner and was first observed at a point approximately one third of the width of the building from the northeast corner, and then spread both east and west across the north face. Sometime later, fires were observed on Floors 8 and 13 with the fire on floor 8 moving from west to east and the fire on Floor 13 moving from east to west. At this time, the fire on Floor 7 appeared to have stopped progressing near the middle of the north face. The fire on Floor 8 continued to move east on the north face, eventually reaching the northeast corner and moving to the east face. Around 4:45 p.m., a photograph showed fires on Floors 7, 8, 9, and 11 near the middle; Floor 12 was burned out by this time. Interview responses indicate that there was no water in the standpipe system supplying the sprinklers in WTC 7.*

Fuel System for Emergency Power

NIST has reviewed the fuel system for emergency power in WTC 7. There were two 12,000 gal fuel tanks below the first floor loading dock and one 6,000 gal above ground tank on the first floor. These tanks supplied fuel to 275 gal day tanks on floors 5, 7, and 8, and a 50 gal day tank on floor 9. In addition, there were two 6,000–gal tanks located below the first floor loading dock with pressurized pipes leading to floor 5.

Floor 5 did not have any exterior windows but it did have exhaust vents for generators near the south and north corners of the building. Any fires that may have burned on this floor would not have been visible in photographic or videographic records, except for smoke at the exhaust vents, which was not observed. The large opening created by the reported gash in the south face may have so altered the air flow on Floor 5 as to vent any smoke generated on this floor out the south face of the building, where overall smoke conditions prevented photographs or other observations. However, there was a pressurized fuel distribution system on the south, west and north floor areas. Given the variability of damage descriptions for the south face from WTC 1 debris impact, Floor 5 is considered a possible fire initiation location, subject to further data and/or analysis on building conditions that improve knowledge of fire conditions in this area.

Finding 1b.5: *The owner of the two 6,000 gal tanks supplying 5th floor generators through a pressurized piping system contracted with an environmental mitigation firm to recover any remaining fuel and to determine the extent of any contamination from fuel leakage from these tanks several months after the collapse. They reported that the tanks had been damaged by debris and were empty. No residual petroleum product or sludge was found in the tanks or piping. Examination of the gravel below the tanks and the sand below the slab on which the tanks were mounted showed some fuel contamination, but none was found in the organic marine silt/clay layer below. Witnesses also reported that the two 6,000 gal fuel tanks were always kept full for emergencies and were full that day. This finding allows for the possibility, though not conclusively, that the fuel may have contributed to a fire on Floor 5.*

1.4 EVACUATION AND EMERGENCY RESPONSE

Buildings are not designed for fire protection and evacuation under magnitude and scale of conditions similar to those caused by the terrorist attacks of September 11, 2001. Prior evacuation and emergency response experience in major events did not include the total collapse of tall buildings such as the WTC towers and WTC 7 that were occupied and in everyday use. Recent experience with major tall building fires suggests that they typically result in burnout conditions, not global building collapse. The intent of building codes is for buildings to withstand design loads without *local* structural collapse until the occupants can escape and the fire service can complete search and rescue operations. The load conditions induced by aircraft impact and the extensive fires on September 11, 2001, which triggered the collapse of the WTC towers, fall outside the norm of design loads considered in building codes.

NIST is interested in determining what factors related to normal building and fire safety considerations, if any, could have saved additional WTC occupant lives on September 11, 2001, or could have minimized the loss of life among the ranks of first responders. This is being accomplished by addressing the following key questions related to occupant behavior, evacuation, and emergency response:

- How did the evacuation technologies and practices affect the resulting fatalities and injuries?
- How did the first responder technologies and practices affect the resulting fatalities and injuries?
- How did the command, control, and communication systems support the activities of the first responders?
- What were the design, capabilities, and performance of the installed active fire protection systems (i.e., fire alarm, sprinkler, and smoke management systems)?
- What were the physical conditions within the buildings associated with occupant safety, tenability, and emergency responder operations?

- How did building design features affect egress and emergency access?

NIST is using multiple sources of data to investigate occupant behavior, evacuation, and emergency response. These sources include:

- Existing published first-person accounts of WTC evacuation; over 725 accounts collected and analyzed.
- Communication tapes from the PANYNJ and NYPD; 1,000-plus hours of taped recordings.
- Filings with the Occupational Safety and Health Administration by survivors and families of victims; about 60 written statements.
- Documents from the PANYNJ, FDNY, NYPD, and others on design of egress and emergency communication systems; WTC evacuation history; WTC evacuation planning and drills; emergency response preparedness and operational data.
- Photographic and videographic data on occupant behavior, evacuation, and emergency response.
- First-person data collection from WTC survivors, current and retired first responders, and families of victims.
- New York City 911 tapes and logs, and transcripts of about 500 interviews with FDNY employees involved in WTC emergency response activities.

Occupant Behavior and Evacuation

NIST is documenting occupant behavior and evacuation efforts by gathering and analyzing information about:

- Evacuation systems, emergency communications, and human factors;
- Occupant location, evacuation experience, and observed building conditions; and
- Interaction between occupants, first responders, and the buildings.

NIST has completed first-person interviews of nearly 1,200 WTC occupants and first responders to collect data on occupant behavior, evacuation, and emergency response, including:

- 803 telephone interviews with occupants of WTC 1 and WTC 2;
- 228 face-to-face interviews of WTC occupants and families of victims, including 28 near the floors of impact in both WTC towers, 33 persons with responsibility within the buildings, 15 who were in elevators, 13 who had a disability, 8 family members of victims, and 7 occupants from WTC 7; further, 8 interviews were conducted with key personnel present inside WTC 7;

- 108 face-to-face interviews of first responders, including 68 from FDNY, 24 from NYPD, 13 from the Port Authority Police Department (PAPD) and other PANYNJ safety and communications personnel, and 3 other building security and fire safety personnel;

- Six focus groups, including a group each from WTC 1 and WTC 2, maintenance and security personnel, floor wardens, people near/above the floor of impact, and mobility-challenged survivors.

Based on information and data gathered during these interviews with *surviving occupants:*:

Finding 2.1: *It is estimated that 17,400 occupants (± 1,200) were present in the WTC towers on the morning of September 11, 2001. The initial population of each tower was similar: 8,900 (± 750) in WTC 1 and 8,500 (± 900) in WTC 2. Of those present on September 11, 2001, 16 percent were also present during the 1993 bombing.*

Finding 2.2: *The average age of surviving occupants of the WTC towers was mid-forties, with a range of ages from their early twenties to mid-seventies. Occupants were twice as likely to be male (65 percent for WTC 1 and 69 percent for WTC 2) as female.*

Finding 2.3: *Two-thirds of WTC 1 surviving occupants had started working in the building during the previous four years (1998-2001), while half of WTC 2 occupants had begun working there during the same time period. The median residence time in WTC 1 was 2 years, while the median in WTC 2 was 3 years. In WTC 1, 4 percent of the occupants had worked in the building since 1975, while there was only one such respondent in WTC 2.*

Finding 2.4: *About 6 percent of the surviving occupants reported a pre-existing limitation to their mobility. These limitations included obesity, heart condition, needing assistance to walk, pregnancy, asthma, being elderly, chronic condition, recent surgery or injury, and other.*

Finding 2.5: *Overall, 7 percent of the surviving occupants reported having special knowledge about the building. These included fire safety staff, floor wardens, searchers, building maintenance, and security staff. Searchers assist the floor wardens in facilitating evacuation.*

Finding 2.6: *Approximately 87 percent of the WTC tower occupants, including more than 99 percent of those below the floors of impact, were able to evacuate successfully. Two-thousand one- hundred fifty-nine building occupants (1,560 in WTC 1 and 599 in WTC 2) and an additional 433 first responders, including security guards, were reported to have lost their lives that day. This does not include aircraft passengers and crew or bystanders.*

Rough initial estimates suggest that about 20 percent or more of those who were in the WTC towers and lost their lives may have been alive in the buildings just prior to their collapse. This estimate—which will be refined as analysis of the data is completed—assumes that nearly all of the first responders and 76 building occupants below the floors of impact but none of the people at or above the floors of impact who may have been alive. Below the floors of impact, there were 72 fatalities reported in WTC 1 and four fatalities reported in WTC 2, not including first responders. It is estimated that were a total of 2,592 building occupants and first responders who were in the WTC towers and lost their lives.

Finding 2.7: *Two-thirds of the surviving occupants reported having participated in a fire drill in the 12 months prior to September 11, 2001, while 17 percent reported that they received no training during that same period. Of those participating in fire drills, 93 percent were instructed about the location of the nearest stairwell. Overall, slightly over half of the survivors, however, had never used a stairwell at the WTC prior to September 11, 2001.*

Finding 2.8: *Overall, about 7,900 surviving occupants evacuated WTC 2 in 73 min (i.e., from the instant the WTC 1 was struck by aircraft until WTC 2 collapsed) while about 7,500 survivors evacuated WTC 1 in 103 min. Thus, the overall evacuation rate in WTC 2 (108 survivors per min) was about 50 percent faster than that in WTC 1 (73 survivors per min). Functioning elevators allowed many survivors to evacuate WTC 2 prior to aircraft impact.*

- *After the first airplane struck WTC 1 and before the second airplane struck WTC 2, the survivors in WTC 2 were twice as likely as those in WTC 1 to have already exited the building (41 percent versus 21 percent). The rate of evacuation completion in WTC 2 was twice the rate in WTC 1 during that same period. The elevators in WTC 2 were functioning at this time, while most of those in WTC 1 were not and survivors could only use the stairways. The stairwells, with partition wall enclosures that provided a 2 h fire-rating but little structural integrity, were damaged in the region of the aircraft impacted floors.*

- *Soon after WTC 2 was struck by the airplane until about 20 min before each building collapsed, the survivors in WTC 2 and WTC 1 had exited at about the same rate (the prior evacuation rate of WTC 1). Most of the elevators in both towers were not functioning at this time, and survivors could only use the undamaged stairways.*

- *During the last 20 min before each building collapsed, the evacuation rate in both buildings had slowed considerably to about one-fifth the immediately prior evacuation rate. This suggests that* for those seeking and able to reach and use undamaged exits and stairways, *the egress* capacity *(number and width of exits and stairways) was adequate to accommodate survivors.*

NIST has utilized existing computer egress models to better understand the evacuation experience on September 11, 2001. While these models were developed using data not indicative of the WTC buildings or events, they can provide some perspective into the relative magnitudes of evacuation times for phased evacuation (as the buildings are designed) and full evacuation of occupants. Three full evacuation scenarios are considered: a typical full capacity building evacuation assuming the WTC tower is fully occupied—with one case considering only tenants and another case considering both tenants and visitors; a full capacity building evacuation of each WTC tower with aircraft impact damage; and a September 11, 2001, capacity evacuation from a WTC tower.

NIST is using two classes of egress models in order to frame the evacuation questions: (1) partial behavior: simulates occupant movement and limited behavioral rules by including delay times, smoke effects, and occupant characteristics; and (2) behavioral: simulates movement and more comprehensive evacuation decisions and activities.

Finding 2.9: *Preliminary results from application of existing computer egress models for a full capacity evacuation of a single WTC tower with 25,000 occupants and visitors indicate a movement time of 2 h* *and 15 min. This is a minimum time estimate since the simulation assumed that there was no survivor delay, continual movement on the stairs, and no damage to the egress system. It was also assumed that elevators were not available. The egress model estimate for a September 11, 2001 capacity evacuation under the same assumptions is about 50 min, which is 2.5 times less than the time estimate for evacuating 25,000 people.*

Finding 2.10: *Given that the actual evacuation time on September 11, 2001 was about 100 min without elevator use, a full capacity evacuation of each WTC tower with 25,000 people would have required about 4 h (or 2.5 times 100 min). To achieve a significantly faster total evacuation at full capacity would have required increases in egress capacity (number and width of exits and stairways).*

Finding 2.11: *Ingress/egress was a tremendous physical challenge for first responders and many occupants; inadequate footwear presented a mobility challenge, particularly for many women. Many people were left shoeless, and their discarded shoes often littered the stairwells.*

NIST also has studied the possibility of roof evacuations from the WTC towers.

Finding 2.12: *A preliminary evaluation indicates that the PANYNJ's evacuation procedures did not include a plan to provide roof rescue for occupants trapped in a building incident at the WTC site. The standard policy was to keep the doors to the roof locked with a key being required to gain roof access. No fire safety procedures explicitly called for opening these doors, including anyone on a "key run." Instead, the standard occupant evacuation procedures and drills required the use of stairwells to exit at the bottom of the WTC towers. The PANYNJ reports that it never advised tenants to evacuate upward.*

Finding 2.13: *There were at least two instances reported on September 11, 2001, where roof access was found to be locked in both WTC towers. In the case of WTC 1, a decedent had called and informed a parent that they had tried to get to the roof and found the door locked. In the case of WTC 2, a decedent had called and informed a spouse that he had tried to get to the roof and found the door locked.*

Finding 2.14: *At least one case was reported on September 11, 2001, where a PANYNJ employee, trapped on Floor 105 of WTC 2, was instructed on the radio (PANYNJ Channel Y) by another PANYNJ employee to go to the roof of the building. The trapped occupant was unable to walk down the stairs, or go to the roof as instructed.*

Finding 2.15: *The NYPD aviation unit arrived at the WTC site soon after WTC 1 was attacked. Despite repeated attempts to examine the possibility of roof rescue, smoke and heat conditions at the top of the WTC towers prevented the conduct of safe roof evacuation operations. A helicopter, attempting to inspect the roof condition and determine if occupants were on the roof, experienced engine temperature increase as it approached WTC 1.*

Finding 2.16: *NYPD has an aviation-training manual to guide roof rescue in high-rise emergencies. The manual is not specific to the WTC. Considering the capacity of typical helicopters and travel times, it is not clear what fraction of the large number of occupants could have been evacuated from the WTC towers prior to their collapse had roof rescue been possible on September 11, 2001.*

The analysis of the first-person accounts collected from occupants by NIST and the evacuation modeling work is ongoing, and NIST will report its additional findings on occupant behavior and evacuation at a later date. That report will incorporate results from the analysis of previously published first-person accounts provided to the media by survivors and information released to the public by the 9-11 Commission.

Emergency Response and Communications

NIST's investigation of fire service technologies and guidelines, and more broadly the emergency response related to firefighting and evacuation on September 11, 2001, seeks to:

1. Document what happened during the emergency response to the attacks on the WTC up until the collapse of WTC 7;
2. Identify issues that need to be addressed in practices, standards, and codes;
3. Identify alternative practices and/or technologies that may address these issues; and
4. Identify technologies and guidelines to advance the safety of first responders in tall building emergencies.

Three FDNY suitcase-based, magnetic Command Boards were set up at the incident site. The unit identification and assignment for each unit that arrives at the scene is written on a magnetic chip and placed on the board. Information related to the location and activities of the units once they are on site are also recorded. One Command Board was set up at the original Incident Command Post in the lobby of WTC 1. The WTC 1 lobby Command Post became an Operations Post when the Incident Command Post moved outside. However, the original Command Board remained in place inside WTC 1 when the Incident Command Post was moved outside. The second Command Board was set up at the fire department's Operations Post in the lobby of WTC 2, and the third Command Board was set up at the new Incident Command Post established by the Chief of Department on West Street in front of the World Financial Center 2 building.

Finding 2.17: *The FDNY suitcase-based, magnetic Command Board system that was generally adequate for normal fire and rescue operations was not adequate for handling the massive operations that were necessary as a result of the terrorist attacks on the WTC. Interviews with FDNY personnel indicated that some FDNY personnel and others entered the towers and were not recorded on the Command Boards. This resulted in the lack of important command information. In addition, each of these Command Boards was damaged, and all were lost with the collapse WTC 2. There was no back-up capability for the Command Boards, and all information related to command, control, and accountability was lost.*

NIST has completed a partial analysis of emergency responder communications including:

- Digital copies of the audio communications tapes recorded by the PANYNJ, including communications from emergency response personnel, maintenance personnel, PAPD personnel, and a recording of the FDNY's city-wide high-rise Channel 7 (PAPD's Channel 30) radio repeater that was located at the WTC; and
- Audio tapes copied from original NYPD communications tapes, including NYPD internal department operations.

FDNY communications recordings from the WTC location on September 11, 2001, are not available because the primary field communication truck was in the shop for repairs, and a backup field communications van was used in its place. The backup van did not have the capability to record the on-scene incident command or tactical communications and was destroyed when the WTC towers collapsed.

The best record of radio communications reflecting fire department operations available to NIST came from the FDNY Channel 7/PAPD Channel 30 tape and first person accounts provided by FDNY personnel during their interviews. The tape provides limited information on FDNY communications and operations at the incident, but it does provide insight into FDNY operations inside WTC 2. FDNY Channel 7/PAPD Channel 30 was a city-wide channel designated by FDNY for use in high-rise building operations. The PANYNJ installed the radio repeater system at the WTC for use by FDNY after the 1993 bombing.

Finding 2.18: *The following findings have been drawn from the first-person interviews with emergency responders regarding telephone communications:*

- *Before the attack occurred, both the landline and cellular systems appeared to be working normally.*

- *Only moments after the first aircraft impacted WTC 1, the landline and cellular telephone systems were stressed by increased caller volume that made it difficult to get messages through. This condition continued for many hours following the attack.*

- *Telephone calls from the WTC to the 911 emergency operators, and statements from various individuals interviewed, show that even though WTC 1 and WTC 2 were severely damaged by aircraft impact and fires, many of the landline telephones in the buildings continued to work up until the collapse of WTC 2.*

- *After the collapse of WTC 2, a number of cellular phone systems were not functional in the area of lower Manhattan.*

- *After the collapse of WTC 2, there were still some landline telephones working within the city block areas adjacent to the WTC site.*

NIST has developed a preliminary chronology, based on analysis of selected communications messages, to provide information concerning (1) dispatch and arrival of emergency response units, (2) evacuation, (3) emergency response operations, (4) emergency response communications, and (5) observations of building conditions.

Finding 2.19: *The following findings have been drawn from the analysis of the emergency responder communication tapes:*

- *After the first aircraft struck WTC 1, there was an approximate factor of 5 peak increase in traffic level over the normal level of emergency responder radio communications, followed by an approximate factor of 3 steady increase in the level of subsequent traffic.*

- *A surge in communications traffic volume made it more difficult to handle the flow of communications and delivery of information.*

- *Roughly a third to a half of the radio messages transmitted during these radio traffic surge conditions were not complete messages or understandable.*

- *Preliminary analysis of the FDNY city-wide high-rise Channel 7 (PAPD Channel 30) recording indicates that the WTC site repeater was operating.*

- *Communications records and interviews with aviation unit personnel indicate that smoke and heat conditions on the top of the WTC towers prevented NYPD helicopters from conducting safe roof evacuation operations.*

- *NYPD aviation unit personnel reported critical information about the impending collapse of the WTC towers several minutes prior to their collapse. No evidence has been found to suggest that the information was communicated to all emergency responders at the scene.*

Finding 2.20: *Several FDNY personnel at the incident site did not think that the high-rise radio repeater was working. This is based on radio communications tests that were conducted by two chief officers working inside WTC 1 when the first command post was being set up in that lobby. This radio communications test was recorded on the FDNY Channel 7/PAPD Channel 30 tape. Following this radio test, a chief officer involved in the test chose to use different channels for command and tactical communications during the disaster. However, as FDNY operations increased in WTC 2, it was determined by FDNY members that the high-rise repeater was functioning, and use of the channel developed.*

Finding 2.21: *While the preliminary NIST analysis indicates that the repeater was operating, there also appears to have been some type of malfunction with the communications equipment that was detected, but not identified, by FDNY officers during the initial test. Three hypotheses are being investigated related to this malfunction: (1) damage to the repeater antenna system located in WTC 5, e.g., changing its direction, (2) failure of the radio handset located at the fire command desk in the lobby of WTC 1, and (3) the volume of the radio hand set not being turned up.*

NIST continues to evaluate the repeater system and its operations, as well as the handheld radios, which were used on September 11, 2001. The findings listed above will be updated and additional findings will be documented when the investigation is complete.

NIST has completed its review of the NYC 9-1-1 tapes and logs and the transcripts of about 500 interviews with FDNY employees involved in WTC emergency response activities. Analysis of this and other information is ongoing.

Finding 2.22: *Based on face-to-face interviews, NIST has determined that first responders— including key incident commanders—did not have adequate information (voice, video, and data) on and an overall perspective of the conditions in the WTC buildings and what was happening elsewhere at the WTC site; interagency information sharing was inadequate.*

NIST continues to analyze all of the data sources (documents, visual images, first-person accounts, and communications records) related to the emergency response activities at the WTC site, including deployment, evacuation, operations, and communication systems and protocols. A future report will document the findings from that analysis.

Fire History of the WTC Towers

NIST has completed a review of the history of post-occupancy fire incidents and identified significant fire incidents—those that exercised the fire suppression systems, specifically multiple sprinklers or one or more standpipes (with or without activation of at least one sprinkler).

The FDNY fire reports and fire investigation records indicate that in areas protected by automatic sprinklers, no fire activated more than three sprinklers. The design area for three sprinklers is a floor area of 63 m^2 (675 ft^2) in light hazard occupancy, such as a high-rise office building as specified in the National Fire Protection Association Standard for the Installation of Sprinkler Systems (NFPA 13).

Many of the fires that occurred were recorded as suspicious or unknown in cause, occurred during off-peak work hours, and involved materials such as trash or paper-based supplies. In cases where sprinklers were activated, the fire department records indicated that the sprinklers either extinguished the fire completely or aided in controlling the spread. In summary:

- 16 significant fires occurred in WTC 1, 2, and 7, with 12 in WTC 1, three in WTC 2, and one in WTC 7. Twelve of the 16 fires occurred between 6 p.m. and 4 a.m. when the number of occupants in the buildings was likely to be small.
- Of the 16 fires and their causes, five were labeled as unlisted or unclassified, six as suspicious or incendiary, two as discarded material, and three as an electrical failure or mechanical failure.
- Of the 16 fires, four were concentrated above the 100th floors and six fires were located in the basements. The other six were distributed throughout the rest of the buildings.
- 31 additional fires occurred in WTC 1 and WTC 2, which involved the use of one standpipe, with 23 in WTC 1 and eight in WTC 2.
- There is no known loss of life as a result of any of these fires (not including the 1993 bombing incident and September 11, 2001, terrorist attacks).

The following significant fires (not including the 1993 bombing incident and September 11, 2001, terrorist attacks) are noteworthy:

- February 14, 1975: Fire started on the 11th floor of WTC 1. Fire damage occurred on the 10th through the 19th floors. Approximately 9,000 ft^2 of 11th floor contents on the southeast corner was destroyed or damaged.
- April 19, 1980: Fire started on the 106th floor of WTC 1. Approximately 300 occupants from the Windows on the World restaurant on the 107th floor were evacuated.

- April 17, 1981: Fire started on the 7th floor of WTC 1. Approximately 1,500 occupants were evacuated from Floors 9 through 23.

Active Fire Protection Systems – Sprinkler Systems

Finding 2.23: *In WTC 1, 2, and 7, primary and secondary water supplies, fire pump size and locations, water storage tanks, and fire department connections provided multiple points of water supply redundancy. The potential for single point failure of the water supply to the fire sprinklers existed at each floor due to lack of redundancy in the sprinkler riser system that provided only one supply connection on each floor. As a result, the water supply to the sprinkler systems or a standpipe serving pre-connected hoses could be interrupted by routine maintenance needs (i.e., shutdown of the riser or standpipe) or by impairment due to deliberate acts to damage the sprinkler riser or standpipe systems. While this lack of redundancy may not have had an impact on September 11, 2001 because the sprinkler system was damaged by aircraft impact, it could have made a difference in other building emergencies.*

Finding 2.24: *Aided by the results of hydraulic modeling of a sprinkler system in WTC 1 and WTC 2—undamaged by aircraft impact and fully operational—the delivered water flow rate available from the automatic sprinkler systems was found to generally exceed the minimum requirements (by a considerable margin) for a high-rise office hazard classification in accordance with NFPA 13. In a number of cases, the amount of available water flow from sprinklers on specific floors was capable of protecting higher fire hazard classes than those associated with light hazard office buildings.*

Active Fire Protection Systems—Fire Alarm Systems

Finding 2.25: *The fire alarm system that was monitoring WTC 7 sent to the monitoring company only one signal (at 10:00:52 a.m. shortly after the collapse of WTC 2) indicating a fire condition in the building on September 11, 2001. This signal did not contain any specific information about the location of the fire within the building. From the alarm system monitor service view, the building had only one zone, "AREA 1." The building fire alarm system was placed on TEST for a period of 8 h beginning at 6:47:03 a.m. on September 11, 2001. Ordinarily, this is requested when maintenance or other testing is being performed on the system, so that any alarms that are received from the system are considered the result of the maintenance or testing and are ignored. NIST was told by the monitoring company that for systems placed in the TEST condition, alarm signals are not shown on the operator's display, but records of the alarm are recorded into the history file.*

Finding 2.26: *The resistance to failure of the fire alarm system communications paths between the fire command station and occupied WTC tower floors could have been enhanced if fiber optic communications cable had been used instead of copper lines. Extensive damage to the towers upon aircraft impact is likely to have cut and short-circuited the wiring of the alarm system network cables. If that occurred, communications between the distributed fire alarm panels, which are components of the integrated fire alarm system, would have been degraded and lost to certain panels depending on the location of those panels. Fiber optic cable is not susceptible to electric short-circuits and would have provided full communications with fire alarm system components, including voice communications systems, to the point where the cable was severed. Electric shorts in the voice communications disable that communication system over the entire cable length affected by the electric short-circuit. During initial engineering design for the fire alarm system in WTC 1 and WTC 2, the PANYNJ requested, but did* *not receive, approval of the City of New York for use of fiber optic communications cable in the system. The NYC code required copper wiring. As a result, ordinary copper wire communication cable was specified.*

A dedicated communications system for emergency responders, known as the "standpipe telephone" system, was installed in the stairwells of WTC 1 and WTC 2. To use the system, a compatible telephone handset was needed. Some firefighters that received handsets at the command post in the lobby of WTC 1 were interviewed as part of the Investigation. Every one of the firefighters interviewed indicated that they did not use the standpipe telephone communication system on September 11, 2001. Due to the loss of firefighters in WTC 2, there is no information about the use of the system in WTC 2.

Active Fire Protection Systems—Smoke Management System

The smoke management system in the WTC towers as designed and documented in the operation manuals consisted of a smoke purge mode using the components of the main HVAC (heating, ventilation, and air-conditioning) system. This system was intended to remove smoke and other gaseous combustion products from the fire area after a fire had been extinguished. This system was to be activated "manually" at the direction of FDNY.

Finding 2.27: *Based on the information reviewed, the smoke management systems were not activated during the fires on September 11, 2001. It was determined that the likelihood of these systems being functional in WTC 1 and WTC 2 was very low due to the damage inflicted by the aircraft impacts. In addition to the significant openings created in the building envelopes, the aircraft impacts are likely to have severed major vertical shafts through which ran electrical power supply and duct risers of the HVAC system, thereby causing the loss of power to the smoke management system air handlers and damage to the vertical HVAC duct risers used to provide smoke management (smoke purge).*

Finding 2.28: *The analysis of smoke flow in WTC 1 and WTC 2 on September 11, 2001, shows that HVAC ductwork was a major path for vertical smoke spread in the buildings. Fire dampers were installed in the systems, but not smoke dampers. Operational combined fire/smoke dampers in the HVAC ductwork on each floor would have provided a barrier to hot gas and smoke penetration into the vertical HVAC shafts in WTC 1 and WTC 2. However, smoke dampers were not available when the towers were built.*

Finding 2.29: *Modeling results show that in WTC 1 and WTC 2 stair pressurization systems would have provided minimal resistance to the passage of smoke had they been installed on September 11, 2001. While the existence of such systems was known when the WTC towers were built, the alternative smoke purge system used in the WTC towers was considered to be equivalent. Multiple stair doors being open for substantial periods of time due to occupant egress and stairway walls damaged by aircraft impact would have resulted in an inability to prevent smoke from entering stairwells.*

1.5 PROCEDURES AND PRACTICES

The 110-story WTC towers were among the world's tallest buildings, while the 47-story WTC 7 represented a more typical tall building. These buildings provide case studies to document, review, and, if needed, improve the procedures and practices used in the design, construction, operation, and maintenance of tall buildings. This investigation objective is independent of other objectives which are focused specifically on the consequences of the attack on September 11, 2001, viz., the building collapses, evacuation, and emergency response. While some findings under this objective are directly relevant to the events of September 11, 2001, others are concerned with general building and fire safety procedures and practices.

NIST seeks to determine the building and fire safety procedures and practices that were used over the life of the WTC buildings and how well those procedures and practices conformed to accepted national building and fire safety practices, standards, and codes. The procedures and practices of interest to the investigation include those related to:

- Design and construction,
- New and innovative design features,
- New and innovative technologies and materials,
- Passive and active fire safety systems,
- Emergency access and egress systems, and
- Structural modifications, inspection, and maintenance.

To provide context for studying the specifications and criteria used for the WTC buildings, NIST has completed a preliminary comparison of building regulatory and code requirements. For the structural system, this comparison included the following building codes:

- New York City Building Code - 1968 edition
- New York State Building Code - 1964 edition
- Chicago Building Code - 1967 edition
- BOCA Basic Building Code - 1965 edition (a national model building code)
- New York City Building Code - 2001 edition

For the fire protection and egress system, the comparison included the five codes listed above plus the 1966 edition of the National Fire Protection Association Life Safety Code (NFPA 101).

Applicable Building Codes

Finding 3.1: *Although not required to conform to NYC codes, the PANYNJ adopted the provisions of the proposed 1968 edition of the NYC Building Code, more than three years before it went into effect. The 1968 edition allowed the PANYNJ to take economic advantage of less restrictive provisions compared* *with the 1938 edition that was in effect when design began for the WTC towers in 1962. The 1968 code:*

- Eliminated a fire tower[5] as a required means of egress;
- Reduced the number of required stairwells from 6 to 3 and the size of doors leading to the stairs from 44 in. to 36 in.;
- Reduced the fire rating of the shaft walls in the building core from 3 h to 2 h;
- Changed partition loads from 20 psf to one based on weight of partitions per unit length (that reduced such loads for many buildings including the WTC buildings); and
- Permitted a 1 h reduction in fire rating for all structural components (columns from 4 h to 3 h and floor framing members from 3 h to 2 h) by allowing the owner/architect to select Class 1B construction for business occupancy and unlimited building height.

Many of these newer requirements, instituted in the 1968 NYC Building Code, are contained in current codes.

Finding 3.2: *The NYC Department of Buildings reviewed the WTC tower drawings in 1968 and provided comments to the PANYNJ concerning the plans in relation to the 1938 NYC Building Code. The architect-of-record submitted to the PANYNJ responses to those comments, noting how the drawings conformed to the 1968 NYC Building Code. NIST continues reviewing documents to determine the level of review conducted by the NYC Department of Buildings and the six specific items identified in that review.*

Finding 3.3: *In 1993, the PANYNJ and the NYC Department of Buildings entered into a memorandum of understanding that restated the PANYNJ's longstanding policy to assure that its facilities in the City of New York meet and, where appropriate, exceed the requirements of the New York City Building Code. The agreement also provided specific commitments to the NYC Department of Buildings regarding procedures to be undertaken by the PANYNJ to assure that buildings owned or operated by the PANYNJ are in conformance with the Building Standards contained in the NYC Building Code. Some salient points included in this agreement and the 1995 enhancement to the agreement are:*

- *Each project would be reviewed and examined for compliance with the Code;*
- *All plans would be prepared, sealed, and reviewed by New York State licensed professional engineers or architects;*
- *The PANYNJ engineer or architect approving the plans would be licensed in the State of New York and would not have assisted in the preparation of the plans; and*

[5] A fire tower (also called a smoke-proof stair) is a stairway that is accessed through an enclosed vestibule that is open to the outside or to an open ventilation shaft providing natural ventilation that prevents any accumulation of smoke without the need for mechanical pressurization.

- *The person or firm performing the review and certification of plans for WTC tenants should not be the same person or firm providing certification that the project had been constructed in accordance with the plans and specifications.*

- *Variances from the Code, acceptable to the PANYNJ, would be submitted to the NYC Department of Buildings for review and concurrence.*

Finding 3.4: *In 1993, the PANYNJ adopted a policy providing for implementation of fire safety recommendations made by local government fire departments after a fire safety inspection of a PANYNJ facility and for the prior review by local fire safety agencies of fire safety systems to be introduced or added to a facility. Later that year, the PANYNJ entered into an agreement with FDNY which reiterated the policy adopted by the PANYNJ, recognized the right of FDNY to conduct fire safety inspections of PANYNJ properties in the City of New York, provided guidelines for FDNY to communicate needed corrective actions to the PANYNJ, assured that new or modified fire safety systems are in compliance with local codes and regulations, and required third-party review of such systems by a New York State licensed architect or engineer.*

Standard Fire-Resistance Tests

Finding 3.5: *Availability of code provisions with detailed procedures to analyze and evaluate data from fire resistance tests of other building components and assemblies to qualify an untested building element. Based on available data and records, no technical basis has been found for selecting the spray-applied fire resistive material (SFRM) used (two competing materials were under evaluation) or its thickness for the large-span open-web floor trusses of the WTC towers. The assessment of the fireproofing thickness needed to meet the 2 h fire rating requirement for the untested WTC floor system evolved over time:*

- *In October 1969, the PANYNJ directed the fireproofing contractor to apply 1/2 in. of fireproofing to the floor trusses.*

- *In 1999, the PANYNJ issued guidelines requiring that fireproofing be upgraded to 1-1/2 in. for full floors undergoing alterations.*

- *Unrelated to the WTC buildings, an International Conference of Building Officials (ICBO) Evaluation Service report (ER-1244), re-issued June 1, 2001, using the same SFRM recommends a minimum thickness of 2 in. for "unrestrained steel joists" with "lightweight concrete" slab.*

Finding 3.6: *Availability of code provisions that require the conduct of a fire resistance test if adequate data do not exist from other building components and assemblies to qualify an untested building element. Instead, several alternate methods based on other fire-resistance designs or calculations or alternative protection methods are permitted with limited guidance on detailed procedures to be followed. Both the architect-of-record (in 1966) and the structural-engineer-of-record (in 1975) stated that the fire rating of the floor system of the WTC towers could not be determined without testing. NIST has not found evidence indicating that such a test was conducted to determine the fire rating of the WTC floor system. The PANYNJ has informed NIST that there are no such test records in its files.*

NIST has awarded a contract to Underwriters Laboratories (UL) to determine the fire resistance rating of the WTC floor system under both as-specified and as-built conditions. The tests, which are expected to be conducted in August 2004, will provide the fire endurance ratings of typical WTC floor construction to evaluate three primary factors: (1) test scale, (2) fireproofing thickness, and (3) thermal restraint. The four tests will be performed as follows:

- 17 ft span assembly, thermally restrained, SFRM thickness of 1/2 in.
- 17 ft span assembly, thermally restrained, SFRM thickness of 3/4 in.
- 35 ft span assembly, thermally restrained, SFRM thickness of 3/4 in.
- 35 ft span assembly, thermally unrestrained, SFRM thickness of 3/4 in.

The first test represents current U.S. practice for establishing a fire endurance rating of a building assembly. The test assembly, fabricated to meet the design of the WTC steel joist-supported floor system, has a span of 17 ft. This span is typical of the floor assembly test furnaces used by the U.S. testing laboratories that routinely conduct the ASTM E119 test for the construction industry. As is common practice, the floor assembly will be tested in the thermally restrained condition. This test will be conducted at UL's Northbrook, Illinois, fire test facility. A second test will be identical except for the thickness of SFRM. The third and forth tests will be at twice the scale of the first two tests, with a span of 35 ft. This span represents a full-scale assembly of the 35 ft floor panel of the WTC floor system. The floor assembly for the third test will be thermally restrained as in the first two tests thereby allowing direct comparison for the determination of the effect of test scale on fire endurance rating. The fourth test will be conducted in the thermally unrestrained support condition which will allow direct comparison of the effect of thermal restraint on the fire endurance rating. The third and fourth tests will be conducted at the UL Canada fire test facility near Toronto.

Building Classification and Fire Rating

Finding 3.7: *Use of the "structural frame" approach, in conjunction with the prescriptive fire rating, would have required the floor trusses, the core floor framing, and perimeter spandrels in the WTC towers to be 3 h fire-rated, like the columns for Class 1B construction in the 1968 NYC Building Code. Neither the 1968 edition of the NYC Building Code which was used in the design of the WTC towers, nor the 2001 edition of the code, adopted the "structural frame" requirement. The "structural frame" approach to fire resistance ratings requires structural members, other than columns, that are essential to the stability of the building as a whole to be fire protected to the same rating as columns. This approach, which appeared in the Uniform Building Code (a model building code) as early as 1953, was carried into the 2000 International Building Code (one of two current model codes) which states: "The structural frame shall be considered to be the columns and the girders, beams, trusses and spandrels having direct connections to the columns and bracing members designed to carry gravity loads." The WTC floor system was essential to the stability of the building as a whole since it provided lateral stability to the perimeter columns and diaphragm action to distribute wind loads to the perimeter columns.*

Finding 3.8: *Availability of technical basis to establish whether the construction classification and fire rating requirements in modern building codes are risk-consistent with respect to the design-basis hazard and the consequences of that hazard. The fire rating requirements, which were originally developed* *based on experience with buildings less than about 20 stories in height, have generally decreased over the past 80 years since historical fire data for buildings suggested considerable conservatism in those requirements. However, for tall buildings, the likely consequences of a given threat to an occupant on the upper floors are more severe than the consequences to an occupant, say, on the first floor. It is not apparent how the current height and area tables in building codes consider the technical basis for the progressively increasing risk to an occupant on the upper floors of tall buildings that are much greater than 200 ft in height. The maximum required fire rating in current codes applies to any building more than about 12 stories in height. There are no additional categories for buildings above, for example, 40 stories and 80 stories, where different building classification and fire ratings requirements may be appropriate, recognizing factors such as the time required for stairwell evacuation without functioning elevators (e.g., due to power failure or major water leakage), the time required for first responder access without functioning elevators, the presence of sky lobbies and/or refuge floors, and limitations on the height of elevator shafts. The 110-story WTC towers, initially classified as Class IA based on the 1938 NYC Building Code, were classified as Class 1B before being built to take advantage of the provisions in the 1968 edition of the code. This re-classification permitted a reduction of 1 h in the fire rating of the components (columns from 4 h to 3 h and floor framing members from 3 h to 2 h).*

Fire Performance of Structures

Finding 3.9: *Structural design does not consider fire as a design condition, as it does the effects of dead loads, live loads, wind loads, and earthquake loads. Current prescriptive code provisions for determining fire resistance of structures—used in the design of the WTC towers and WTC 7— are based on tests using a standard fire that may be adequate for many simple structures and for comparing the relative performance of structural components in more complex structures. A building system with 3 h rated columns and 2 h rated girders and floors could last longer than 3 h or shorter than 2 h depending upon the performance of the structure as a 3-dimensional system in a real fire. The standard tests cannot be used to evaluate the actual performance (i.e., load carrying capacity) in a real fire of the structural component, or the structure as a whole system, including the connections between components. Performance-based code provisions and standards are not available for use by engineers, as an alternative to the current prescriptive fire rating approach, to (1) evaluate the system performance of tall-building structures under real fire scenarios, and (2) enable risk consistent design with appropriate thickness of passive protection being provided where it is needed on the structure. Standards development organizations, including the American Institute of Steel Construction, have initiated development of performance-based provisions to consider fire effects in structural design.*

Finding 3.10: *Availability of detailed procedures to select appropriate design-basis fire scenarios to be considered in the performance-based design of the sprinkler system, compartmentation, and passive protection of the structure. The standard fire in current prescriptive fire resistance tests is not adequate for use in performance-based design. While the NFPA 5000 model building code contains general guidance on design fire scenarios (the IBC Performance Code contains no such guidance), the details of the scenarios are left to the fire engineer and regulatory official. The three major scenarios that are not considered adequately are: frequent but low severity events (for design of sprinkler system), moderate but less frequent events (for design of compartmentation), and a maximum credible fire (for design of passive fire protection on the structure). The maximum credible fire scenario for passive protection of structures would assume that the sprinkler system is compromised or overwhelmed and that there is no active firefighting. These building-specific representative fire scenarios are similar in concept, though not* *identical, to the approach used in building design where the performance objectives and design-basis of the hazard are better defined (e.g., a two-level design that includes an operational event with a 10 percent probability of occurrence in 50 years and a life safety event with a 2 percent probability of occurrence in 50 years). The design-basis fire hazards for the WTC towers and WTC 7 are unknown, and it is difficult to evaluate the performance of the fire protection systems in these buildings under specific fire scenarios.*

Finding 3.11: *Availability of code provisions to ensure that structural connections are provided the same degree of fire protection as the more restrictive protection of the connected elements. The provisions that were used for the WTC towers and WTC 7 did not require specification of a fire-rating requirement for connections separate from those for the connected elements. It is not clear what the fire rating of the connections were when the connecting elements had different fire ratings.*

Finding 3.12: *Availability of technical basis to establish whether the minimum mechanical and durability related properties of SFRM are sufficient to ensure acceptable in-service performance in buildings. While minimum bond strength requirements exist, there are no serviceability requirements for such materials to withstand typical shock, impact, vibration, or abrasion effects over the life of a building. There are existing testing standards for determining many of these properties, but the technical basis is insufficient to establish serviceability requirements. Knowledge of such serviceability requirements is relevant to determine the post-impact fireproofing condition of the WTC towers.*

Finding 3.13: *Availability of validated and verified tools for use in performance-based design practice to analyze the dynamics of building fires and their effects on the structural system that would allow engineers to evaluate structural performance under alternative fire scenarios and fire protection strategies. Existing tools are either too simplified to adequately capture the performance of interest or too complex and computationally demanding, and lack adequate validation. While considerable progress has been made in recent years, significant work remains to be done before adequate tools are available for use in routine practice. NIST has had to further develop and validate existing tools to investigate the fire performance of the WTC towers and WTC 7.*

Structural Integrity

Finding 3.14: *Availability of explicit structural integrity provisions to mitigate progressive collapse. Federal agencies have developed guidelines to mitigate progressive collapse and routinely incorporate such requirements in the construction of new federal buildings. The United Kingdom incorporates such code requirements for all buildings. New York City adopted by rule in 1973 a requirement for buildings to resist progressive collapse under extreme local loads. The rules, which were adopted after the WTC towers were built but before WTC 7 was built, applied specifically to buildings that used precast concrete wall panels and not to other types of buildings. As stated in Finding 1b.1, the current working hypothesis for the collapse of the 47-story WTC 7, if it remains viable upon further analysis, would suggest that it was a classic progressive collapse.*

Finding 3.15: *Availability of minimum structural integrity provisions for the means of egress (stairwells and elevator shafts) in the building core that are critical to life safety. In most tall buildings the core is designed to be part of the vertical gravity load carrying system of the structure. However, in many of those buildings, especially in regions where earthquakes are not dominant, the core may not be part of* *the lateral load carrying system of the structure. Thus, the core may be designed to carry only vertical gravity loads with no capacity to resist lateral loads, i.e., overturning moment and shear loads. In such situations, the structural designer may prefer the use of partition walls over structural walls in the core area to reduce building weight. The decision to have the core carry a specified fraction of the lateral design loads or be made part of a dual system to carry lateral loads, each of which would enhance the structural integrity of the core if structural walls were used, is left to the discretion of the structural engineer. Alternatively, stairway/elevator cores built with concrete or reinforced concrete block, which are not part of the lateral load carrying system, may be able to provide sufficient structural integrity if they meet, for example, the hose-stream impact test already required by ASTM E 119, or other more appropriate test. In the case of the WTC towers, the core had 2 h fire-rated partition walls with little structural integrity and the core framing was required to carry only gravity loads. Had there been a minimum structural integrity requirement to satisfy normal building and fire safety considerations, it is conceivable that the damage to stairways, especially above the floors of impact, may have been less extensive.*

Finding 3.16: *Availability of standards and code provisions for conducting wind tunnel tests and for the methods used in practice to estimate design wind loads from test results. Building codes allow the determination of wind pressures from wind tunnel tests for use in design. Such tests are frequently used in the design of tall buildings. Results of two sets of wind tunnel tests conducted for the WTC towers in 2002 by independent commercial laboratories as part of insurance litigation, and voluntarily provided to NIST by the parties to the litigation, show large differences, of as much as about 40 percent, in resultant forces on the structures, i.e., overturning moments and base shears. Independent reviews by a NIST expert on wind effects on structures and a leading engineering design firm contracted by NIST indicated that the documentation of the test results did not provide sufficient basis to reconcile the differences. In addition, the wind loads estimated from these tests are about 20 percent to 60 percent higher than those apparently used in the original design of the WTC towers, also obtained from wind tunnel testing. NIST is conducting an independent analysis to establish the baseline performance of the WTC towers under the original design wind loads and will compare those wind load estimates with then-prevailing code requirements. Wind loads were a major governing factor in the design of structural components that made up the frame-tube steel framing system.*

Compartmentation and Sprinklers

Building fire protection is based on a four-level hierarchical strategy comprising detection, suppression (sprinklers and firefighting), compartmentation, and passive protection of the structure.

- Detectors are typically used to activate fire alarms and notify building occupants and emergency services.

- Sprinklers are designed to control small and medium fires and to prevent fire spread beyond the typical water supply design area of about 1,500 ft^2.

- Compartmentation mitigates the horizontal spread of more severe but less frequent fires and typically requires fire-rated partitions for areas of about 7,500 ft^2. Active firefighting also covers up to about 5,000 ft^2 to 7,500 ft^2.

- Passive protection of the structure seeks to ensure that a maximum credible fire scenario, with sprinklers compromised or overwhelmed and no active firefighting, results in burnout, not overall building collapse. The intent of building codes is also for the building to withstand local structural collapse until occupants can escape and the fire service can complete search and rescue operations.

Compartmentation of spaces has long been a cornerstone to building fire safety to limit fire spread. The WTC towers initially had 1 h fire-rated partitions separating tenants (demising walls) that extended from the floor to the suspended ceiling, not the floor above (the ceiling tiles were not fire rated). Over the years, these partitions were replaced with partitions that were continuous from floor to floor (separation wall) as required by the 1968 NYC Building Code. Some partitions had not been upgraded by 1997, and a consultant recommended to the PANYNJ that it develop and implement a survey program to assure that the remediation process occurred as quickly as possible. It appears that with few exceptions, nearly all of the floors not upgraded were occupied by a single tenant, and it is not clear whether separation walls would have mattered in terms of meeting the 1968 code. The PANYNJ adopted guidelines in 1998 that required such partitions to provide a continuous fire barrier from top of floor to underside of slab.

Finding 3.17: *Building codes typically require 1 h fire-rated tenant separations but do not impose minimum compartmentation requirements (e.g., 7,500 ft^2) for buildings with large open floor plans to mitigate the horizontal spread of fire. This is the case with both the 1968 NYC Building Code, which did not require above-ground sprinklers, and the 2001 NYC Building Code, which requires sprinklers. The sprinkler option was chosen for the WTC towers in preference to the compartmentation option in meeting the subsequent requirements of Local Law 5 adopted by New York City in 1973. Thus, if there was only one tenant on a WTC floor there would be no horizontal compartmentation requirement. Conversely, if there were a large number of tenants on a WTC floor, it would be highly compartmented with separation walls. The affected floors in the WTC towers were mostly open—with a modest number of perimeter offices and conference rooms and an occasional special purpose area. Some floors had two tenants and those spaces, like the core areas, were partitioned (slab to slab). Photographic and videographic evidence confirms that even non-tenant space partitions (such as those that divided spaces to provide corner conference rooms) provided substantial resistance to fire spread in the affected floors. For the duration of about 50 to 100 min prior to collapse of the WTC towers that the fires were active, the presence of undamaged 1 h fire-rated compartments may have assisted in mitigating fire spread and consequent thermal weakening of structural components.*

Finding 3.18: *Availability of state and local building regulations for early installation of sprinklers in existing buildings, not as an option in lieu of compartmentation. Functioning sprinklers can provide significant improvement in safety for most common building fires and prevent them from becoming large fires. NYC promulgated local laws in 1973 and 1984 to encourage installation of sprinklers in new buildings, and is now considering a law to require sprinklers in existing buildings. The WTC towers were fully sprinklered by 2001, about 30 years after their construction. Sprinklering of the tenant floors in the WTC towers was completed by October 1999, while sprinklering of the sky lobbies was still underway at that time. The sprinkler system was installed in three phases. Phase 1 was completed during initial building construction and included the sub-grade areas. Phase 2 was done in 1976, in compliance with Local Law 5, and included sprinklering the corridors, storage rooms, lobbies, and certain tenant spaces. Phase 3 was begun in 1983 and completed in 2001 and resulted in fully sprinklering the complex.*

Finding 3.19: *Modern building codes allow a lower fire rating for structural elements when a building is sprinklered. This trade-off provides an economic incentive to encourage installation of sprinklers. Sprinklers provide better intervention against small and medium fires, fires which are more likely to occur than a WTC disaster, as long as the water supply is not compromised and there is redundant technology in place. The required technical basis is not available to establish whether the "sprinkler trade-off" in current codes adequately considers fire safety risk factors such as: (1) the complementary functions of sprinklers and fire-protected structural elements, (2) the different fire scenarios for which each system is designed to provide protection, and (3) the need for redundancy should one system fail. It is noteworthy that the British Standards Institution (BSI) has established a group to review all the sprinkler trade-offs contained in their standards. While the classification and fire rating of the WTC towers did not take advantage of the sprinkler-tradeoff since such provisions were not contained in the 1968 NYC Building Code, had such provisions existed, they would have required a lower fire rating for many WTC building elements.*

Occupant Behavior and Evacuation

The capacity of egress systems in very tall buildings is based on the phased evacuation concept, where occupants are evacuated first from the three floors closest to the emergency (e.g., fire), while others wait their turn. Such systems require a voice communication system to manage the process from a fire command center and, e.g., in New York City, fire wardens on each floor directing the flow. These systems are not designed to accommodate a total or full emergency evacuation of the building.

There were at least three instances where a full evacuation of the WTC towers was ordered; a 1977 terrorist threat associated with bombings in two midtown Manhattan buildings, during the 1993 bombing, and on September 11, 2001. During the 1977 event, a full evacuation of the WTC complex was ordered at 11:45 a.m., and fire safety teams searched and evacuated 35,000 occupants. The evacuation was orderly, and no one was injured. The WTC complex was reopened to the public at 3:00 p.m. In addition, about 1,500 people were evacuated from 15 floors of WTC 1 during a fire on the morning of April 17, 1981.

Sufficient data do not exist on the frequency with which full evacuations are conducted in buildings not at risk for terrorist attacks and whether this frequency has increased since September 11, 2001. In one of the three instances, the WTC towers had to be fully evacuated even though the terrorist threat was to other remote buildings in the city. Based on NIST interviews of WTC survivors and anecdotal data reported to the 9-11 Commission, it appears that since September 11, 2001, building occupants may be more likely to evacuate even when the safety risk at their location may not be sufficient to require them to evacuate. It is not clear how widespread this sentiment is among the general population that did not experience the events of September 11, 2001 directly.

Finding 3.20: *Availability of technical basis for the design of egress systems. Current prescriptive methods (e.g., unit width or inches per person) for minimum stair width or number of stairs do not provide information on the target performance to be achieved. For example, what would be the evacuation rate or time, for a given occupant population, considering travel distance, remoteness requirements, and human factors such as occupant size (reflecting current population data), stairwell environmental conditions, visibility, and congestion. Also, the technical basis for the "sprinkler trade-off") in egress specifications (generally a doubling of allowed travel distance is not available).*

Further, proposals for increases in stair width do not consider the effect of doors in limiting the flow. Also, proposals for increases in the number of stairs do not balance the need to meet remoteness requirements (physical separation of stairways that are located in separate enclosures) while possibly permitting scissor stairs (two separate stairways within the same enclosure and separated by a fire rated partition). Scissor stairs are credited as a single stair but provide additional capacity and additional doors that achieve real increases in evacuation rate with only minor impact on leasable space. The egress capacity in the WTC towers was based on the unit-width method contained in the 1968 NYC Building Code; it is not possible to assess the adequacy of the resulting egress capacity to achieve a target performance (e.g., evacuation rate or time) under a design-basis evacuation event. Further, although the NYC code permitted scissor stairs—which are prohibited in most other codes—none were used in the WTC towers or WTC 7.

Finding 3.21: *Consideration of counterflow, e.g., due to first responder emergency access, in the design of egress systems. For typical short height buildings, the occupants are evacuated from the affected floors within a matter of several minutes, before first responders arrive and climb up the stairs. While such evacuation still would be ongoing after arrival of first responders in taller buildings, NIST interviews with WTC occupants suggest that on September 11, 2001, with about one-third of building occupants present, there were only occasional encounters with first responders, and counterflow was not a significant issue. This finding is consistent with the Finding 2.8—based on occupant first-person interviews—related to adequacy of the egress capacity in the WTC towers on September 11, 2001.*

Use of Elevators in Emergencies

Finding 3.22: *With a few special exceptions, building codes in the United States do not permit the use of fire-protected elevators for routine emergency access by first responders or as a secondary method (after stairwells) for emergency evacuation of building occupants. The use of elevators by first responders would additionally mitigate counterflow problems in stairwells. While the United States conducted research on specially protected elevators in the late 1970s, the United Kingdom has required such "firefighter lifts," located in protected shafts, for a number of years. Without functioning elevators (e.g., due to a power failure or major water leakage), first responders carrying gear typically require about a minute per floor to reach an incident using the stairs. While it is difficult to maintain this pace for more than about the first 20 stories, it would take a first responder about an hour to reach, for example, the 60th floor of a tall building if that pace could be maintained. Such a delay, combined with the resulting fatigue and physical effects on first responders that were reported on September 11, 2001, would make firefighting and rescue efforts difficult even in tall building emergencies not involving a terrorist attack. Each of the WTC towers had 100 elevators, and WTC 7 had 38 elevators. By code, the elevators could not be used for fire service access or occupant egress during an emergency since they were not fire-protected, nor were they located in protected shafts. The elevators were equipped through normal modernization with fire service recall. Most were damaged by the aircraft impacts; though prior to the impact in WTC 2 the elevators were functioning and contributed greatly to the much faster initial evacuation rate in WTC 2 as stated in Finding 2.8.*

Building Practices

Finding 3.33: *While the PANYNJ entered into agreements with the NYC Department of Buildings in the 1990s (with regard to conformance of PANYNJ buildings constructed in New York City to the NYC*

Building Code), the PANYNJ did not yield jurisdictional authority for regulatory and enforcement oversight to the New York City Department of Buildings. The PANYNJ was created as an interstate entity, under a clause of the U.S. Constitution permitting compacts between states, and is not bound by the authority of any local, state, or federal jurisdiction.

Finding 3.34: *Availability of rigorous field application and inspection provisions and regulatory requirements to assure that the as-built condition of the passive fire protection, such as SFRM, conforms to conditions found in fire resistance tests of building components and assemblies. For example, provisions are not available to ensure that the as-applied average fireproofing thickness and variability (reflecting the quality of application) is thermally equivalent to the specified minimum fire proofing thickness. In addition, requirements are not available for in-service inspections of passive fire protection during the life of the building. The adequacy of the fireproofing of the WTC towers posed an issue of some concern to the PANYNJ over the life of the buildings, and the availability of accepted requirements and procedures for conducting in-service inspections would have provided useful guidance.*

Finding 3.35: *State and local jurisdictions do not require retention of documents related to the design, construction, operation, maintenance, and modifications of buildings, with few exceptions. These documents are in the possession of building owners, contractors, architects, engineers, and consultants. Such documents are not archived for more than about 6 to 7 years and there are no requirements that they be kept in safe custody physically remote from the building throughout its service life. In the case of the WTC towers, the PANYNJ and its contractors and consultants maintained an unusually comprehensive set of documents, a significant portion of which had not been destroyed in the collapse of the buildings but could be assembled and provided to the investigation. In the case of WTC 7, the situation was more typical of current practice, and a significant portion of the documents could not be assembled since they were lost in the collapse of the building. However, NIST has adequate information for its investigation. Neither the original general contractor nor the architects was able to supply more than a few documents.*

Finding 3.36: *The architect is responsible for specifying the fire protection and designing the evacuation system in current building practice. The structural engineer is not required to evaluate and certify that the passive fire protection is adequate to protect the structural system. In accordance with established practice, the structural engineer was not responsible for the passive fire protection in the design of the WTC tower structures. In addition, there is no requirement for a fire protection engineer to be part of the team designing the overall fire protection (including detection, suppression, compartmentation, and passive fire protection) and evacuation systems for the building. A change in this respect is already underway for signature/iconic buildings, where it is becoming more common for a fire protection engineer to be included in the design team. In the case of the WTC towers, the building owner played a significant role in specifying the fire protection and evacuation systems; a fire protection engineer was not part of the original design team. There are only a few academic degree programs or continuing education programs that qualify engineers (or architects) to evaluate the fire performance of structures. The current state-of-practice is not sufficiently advanced for engineers to routinely analyze the performance of a whole structural system under a prescribed design-basis fire scenario.*

1.6 APPROACH TO RECOMMENDATIONS

In the United States, state and local governments are responsible for promulgating and enforcing building and fire regulations. While states are increasingly adopting a single, uniform set of statewide regulations, in many instances major cities and counties adopt their own regulations. The national organization representing state building officials is the National Conference of States on Building Codes and Standards (NCSBCS)—a body of the National Governors Association—and that representing building officials of major local jurisdictions is the Association of Major City/County Building Officials (AMCBO).

With some exceptions, the state and local regulations are based on national model building and fire codes developed by private sector organizations, the International Code Council (ICC) and the NFPA. The model codes, in turn, reference voluntary consensus standards developed by a large number of private sector standards development organizations (SDOs). They include organizations such as NFPA, ASTM International, the American Society of Civil Engineers (ASCE), the American Institute of Steel Construction (AISC), and the American Concrete Institute (ACI). The SDOs are accredited by the American National Standards Institute (ANSI).

Other key stakeholder groups involved in the design, construction, operation, and maintenance of buildings include organizations representing building owners and managers, real estate developers, contractors, architects, engineers, suppliers, and insurers.

NIST is a non-regulatory agency of the U.S. Department of Commerce. NIST does not set building codes and standards, but provides technical support to the private sector and other government agencies in the development of U.S. building and fire practices, standards, and codes. NIST recommendations are given serious consideration by private sector organizations that develop national standards and model codes – which provide minimum requirements for public welfare and safety. The model codes become regulation when adopted by state and local governments.

The NIST building and fire safety investigation of the WTC disaster has not yet formulated recommendations under this objective. However, in formulating its recommendations, NIST will consider the following:

- Findings from the first three independent investigation objectives related to building performance, evacuation and emergency response, and procedures and practices.

- Whether findings relate to the unique circumstances surrounding the terrorist attacks of September 11, 2001, or to normal building and fire safety considerations, including evacuation and emergency response?

- What technical solutions are needed, if any, to address potential risks to buildings, occupants, and first responders, considering both identifiable hazards and the consequences of those hazards?

- Whether the risk is in all buildings or limited to certain building types (e.g., height and area, structural system), buildings that contain specific design features, iconic/signature buildings, or buildings that house critical functions?

NIST urges organizations responsible for building and fire safety at all levels to carefully consider the interim findings contained in this report. NIST welcomes comments from technical experts and the public on the interim findings presented herein. Comments can be sent by e-mail to wtc@nist.gov, facsimile to 301-975-6122, or regular mail to WTC Technical Information Repository, Stop 8610, 100 Bureau Drive, Gaithersburg, MD 20899-8610.

In its final report, a draft which is expected to be released in December 2004, NIST will recommend appropriate improvements in the way buildings are designed, constructed, maintained and used. It will be important for those recommendations to be thoroughly and promptly considered by the many organizations responsible for building and fire safety. As a part of NIST's overall WTC response plan, the Institute has begun to reach out to those organizations to pave the way for a timely, expedited consideration of recommendations stemming from this investigation. NIST also already has expanded its research in areas of high priority need.